Risk aversion and technology portfolios

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Abstract

The choice of a portfolio of technologies by risk-averse firms is analyzed. Two technologies with random marginal costs are available to produce a homogeneous good. If the risks associated to the technologies are correlated firms might invest in a technology with a negative expected return or conversely might not invest in a technology with a positive expected return. If the technology with the lower expected cost is more risky than the other technology this technology can be driven out of the firms' portfolio if risks are highly correlated. With imperfect competition the portfolios of firms are different, and difference in risk aversion can explain a full specialization of the industry, the less risk averse firms using the low cost technology and the more risk averse firms the other one. The framework is used to discuss the issue of investment in electricity markets.

keywords: risk aversion, investment, technology mix

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1 introduction

In many industries, firms face random output and input prices. The electricity industry is a particularly striking example, as important uncertainties surround the prices of fossil fuels and CO_2 emissions as well as the subsidy schemes that support renewable energies, the time to build new nuclear plants, and the cost of efficient coal plants and carbon capture and storage facilities. These uncertainties are likely to influence the overall supply and the technology mix chosen by firms, in particularly if these firms are risk-averse. One issue is whether investment in an efficient technology could be deterred because of risk and risk-aversion and if so, how this phenomenon could be linked to industry structure.

In the present paper, the supply of an industry composed of risk-averse firms is analyzed. There are two technologies available and each firm must decide how much to produce with each technology. One technology has a lower expected marginal cost than the other, and, in a sense, is more efficient. However, the firm could diversify its portfolio by investing in the other more costly technology to reduce its risk. The influence of correlation is emphasized. As the supply of a single firm is described, it is shown that the higher the price the lower the share of the efficient (cheap) technology in its technology "portfolio" and if risks are sufficiently correlated, the firm does not invest in the efficient technology, but instead solely invests in the inefficient one if the output price is large. Thus, risk and risk-aversion can explain how an efficient technology is driven out of a firm' portfolio. Industry equilibrium with price-taking and Cournot competitors is described. With perfect competition, all firms have the same portfolio of technologies. The total industry supply is determined by the aggregate risk-aversion of the industry and the demand function. The risk-aversion of a particular firm only determines its size, not the composition of its portfolio. The similarity of all firms' portfolios is reminiscent of a feature of the Capital Asset Pricing Model: any investor's portfolio is a combination of the market portfolio and a risk-free asset (see Sharpe, 1991, for a nice exposition). With Cournot competition, it is shown that this feature does not hold, as less risk-averse firms are not only larger but also more efficient. The relation of this work with the general literature is first reviewed, and then the case of technology choices in electricity markets is further discussed.

The assumption of profit maximizing and risk-neutral firms is central to the Arrow-Debreu economy. However, several theoretical reasons could be advanced to explain that firms act *as if* they were risk-averse (see Banal-Estanol and Ottaviani, 2006, for a review) and several empirical studies support such claims.[1] Risk-aversion is likely to play a crucial role when the firm must make long-term decisions, such as investment choice. The influence of risk-aversion on a firm's production decisions has been analyzed in numerous contexts and several authors have analyzed the influence of output price uncertainty on a competitive risk-averse firm's production (Dhrymes, 1964; McCall, 1967; Baron, 1970; Sandmo, 1971).[2] The main conclusions are that the more risk-averse the firm, the less it produces, and a risk-averse firm produces less as uncertainty increases.

With random input prices, Stewart (1978) shows that a risk-averse firm over-invests in riskless factors.[3] Input price risks have also been analyzed by Blair (1974) and Okuguchi (1977), but none of these analysis address the issue of technological diversification and they all neglect an important consequence of correlation between input prices that is central to the present analysis. Without correlation, the profit of a firm is negatively correlated with an input price. This correlation explains that the firm tends to under-invest in a risky input–i.e. the marginal productivity of this input is lower than the ratio of the expected input price and the output price. This result is not generally true if correlations are considered. If the price of an input is negatively correlated with the price of another it is possible that the profit be negatively correlated with one price implying an over-investment in the corresponding input.

In electricity markets, the existence of a technology mix is fundamen-

[1]For instance risk-aversion can explain corporate hedging activity (Amihud and Lev, 1981; Nance et al., 1993; May, 1995), and Wolak and Kolstad (1991) have empirically investigated how risk-aversion explains the choices of risky coal suppliers by japanese firms.

[2]Appelbaum and Katz (1986) and Haruna (1996) studied long-run industry equilibrium. Bradburd (1980a,b) considered the production choices of a risk-averse conglomerate. The assumption of firms risk-aversion has also been used to analyze the use by firms of financial futures and option contracts (McKinnon, 1967; Newbery and Stiglitz, 1981; Moschini and Lapan, 1995) and vertical integration (Hirshleifer, 1988; Aïd et al., 2011). The monopoly situation has been analyzed by Baron (1971) and Leland (1972). Strategic interactions have received attention more recently, notably by Tessitore (1994), Wambach (1999), Asplund (2002) and Banal-Estanol and Ottaviani (2006).

[3]Batra and Ullah (1974) analyzes how the uncertainty on output price influence the choice of inputs, however if the output quantity is chosen before uncertainty is resolved uncertainty has only an indirect effect on input choices (Holthausen, 1976; Mayer, 1978).

tally related to demand variability and the difference in the cost structures of technologies Green (2006). This issue is not considered here. The model constructed in this study, when used to think about an electricity market, should be interpreted as describing competition for base-load production. The issue is not the anticipated and well-known time variability of demand but the implications of producers being risk-averse toward their choice of base-load units. Risk and risk-aversion are considered as one possible explanations for a potential lack of investment in total capacity or in a particular kind of technology in an electricity market.

Neuhoff and De Vries (2004) provided a formal analysis of the influence of risk and producers risk-aversion on their investment choice with a single technology. Concerning the technology mix, the use of financial portfolio techniques (Markowitz, 1952) to evaluate the diversification of power producing utilities was first used in the 'regulated era' and was initiated by Bar-Lev and Katz (1976) to evaluate the mix of fossil fuels of regulated electricity utilities. Such a formal analysis has also been used by several authors to evaluate national portfolios (Humphreys and McClain, 1998; Awerbuch, 2000; Awerbuch and Berger, 2003; Jansen et al., 2006). Roques et al. (2008) used this approach to evaluate firms' investment decisions and determined the efficiency frontier (expected return versus variance) of portfolios comprised of combined cycle gas turbine (CCGT), coal and nuclear plants; they established that the positive correlation between electricity and gas prices favors investment in CCGT. This issue is of particular interest given that the technology of CCGT was one of the driver of electricity liberalization (Green and Newbery, 1992; Newbery, 1998) and that nuclear is considered to play a key role in the future generation mix (EPACT, 2005; Department for Business, 1993) although producers seem reluctant to invest in this technology (Department for Business, 1993; Finon and Roques, 2008). Fan et al. (2010) and Ehrenmann and Smeers (2011) used numerical simulation of an electricity industry equilibrium to assess the influence of generators' risk-aversion on the total capacity built and on the technology mix.[4] They consider several sources of uncertainty among which the CO_2 regulation.

The present paper offers a formal analysis of the determinants of the portfolio of a risk-averse firm, and, analyzes formally the industry equilib-

[4]Most studies of technologies portfolio in electricity markets either at the country or the firm level, consider a fixed aggregate quantity of capacity (expressed in Watt) and determine the portfolio of technologies that maximize return subject to a constraint on standard deviation.

rium under perfect and imperfect competition. The generality of the analysis allows to consider numerous relevant situations among which the case of a positive correlation between electricity price and CCGT cost. One may be skeptical about the importance of risk-aversion and hedging as major determinants of investment choice and particularly as possible deterrents of investment in specific technologies (e.g. nuclear or renewable) as, a priori, risk is a second order phenomenon, compared to expected costs and prices. However, risk and correlation could play a significant role and it is shown in this study that, even without any technical non-convexities (decreasing return to scale, minimal size, startup cost etc...) if firms are risk averse, risk could theoretically disqualify an efficient technology. Furthermore, the industry equilibrium is analyzed and it is shown that if competition is perfect all firms have the same portfolio of technologies, although less risk-averse firms produce more than others. This result contradicts the empirical observation in the EU where firms have different technology mixes (D.G.Competition, 2007). However, if competition is imperfect, it is shown that the portfolio of firms differ, the less risk-averse firms are not only bigger but also more efficient. At equilibrium, it is possible that big firms specialize in the efficient technology while small firms specialize in the inefficient one. This specialization is endogenous and not assumed, big firms are not big because they have a privileged access to the efficient technology (as it is the case in Meunier, 2010), but, because they are less risk-averse. And small firms are not prevented from using the efficient technology because of some fixed cost but solely because of risks and their risk-aversion.

The rest of the paper is organized as follows. In the next section, the model is introduced. The model if then used to analyze first the supply of a single firm (Section 3) and then the market equilibrium with either perfect competition or Cournot competition (Section 4). Finally, the framework is used to discuss the specific issues of the choice between nuclear and gas (Section 5). Section 6 concludes.

2 Model

The model developed is quadratic: marginal costs are constant with respect to production, uncertainty is additive and each firm's objective is represented by a mean-variance utility function. A good, sold at a price p, could be produced with two technologies labeled $t = 1, 2$ with marginal cost: $c_t + \theta_t$, where θ_t are random variables with $\mathbb{E}\theta_t = 0$. Standard deviations are denoted by σ_t for $t = 1, 2$, covariance by σ_{12} and the correlation by $\rho = \sigma_{12}/\sigma_1\sigma_2$, it is between -1 and 1 as $\sigma_{12} \leqslant \sigma_1\sigma_2$. It is assumed that the random variables are not perfectly correlated, i.e. $\rho \neq -1, 1$. When t is used to denote one of the technology s is used for the other $s, t = 1, 2$ and $s \neq t$. The expected marginal cost of technology 1 is assumed lower than the expected marginal cost of technology 2, $c_1 < c_2$ and thus this technology is called "efficient" and technology 2 "inefficient". A risk-neutral industry would only use technology 1 and produce a quantity that would equalize the price with the expected cost of technology 1. With a slight abuse of language, a portfolio is qualified as more efficient the larger is its share of technology 1.

The good is produced by an industry consisting of a set I of n firms. The production of firm i in I is denoted by q^i, which is the sum of its production with technology 1, q_1^i, and technology 2, q_2^i. The demand side is represented by the price function $p(Q)$, where Q is the aggregate quantity produced by all firms:

$$Q = \sum_{i \in I} q^i = \sum_{i \in I} \left[q_1^i + q_2^i \right]. \tag{1}$$

This price function is continuous and decreasing, and it is positive and twice differentiable for Q in $[0, \bar{Q}]$, with $\bar{Q} > 0$ and null for $Q > \bar{Q}$. It satisfies the following condition :

$$\forall Q \in [0, \bar{Q}], P'' + P'Q > 0 \tag{A}$$

This last assumption, which is common in the industrial organization literature, implies that the marginal revenue of a firm is decreasing with respect to the production of its rival. Thus, quantities are strategic substitutes, and the existence and uniqueness of Cournot equilibria are ensured if firms have convex costs. It is equivalent to assume that functions $x \to p'(x + y)x$ are decreasing for all y.

For i in I the profit of firm i is as follows:

$$\pi^i(p, q_1^i, q_2^i, \theta_1, \theta_2) = pq^i - (c_1 + \theta_1)q_1^i - (c_2 + \theta_2)q_2^i. \tag{2}$$

The firm is assumed to maximize a mean-variance utility function where $\lambda^i > 0$ represents its risk aversion:

$$U(p, q_1^i, q_2^i) = \mathbb{E}\pi^i - \frac{\lambda^i}{2}\mathrm{var}(\pi^i) \tag{3}$$

The risk is only represented by the variance of the firm's profit, and the firm's risk-aversion measures how the firm weights the variance compared to the expected profit.

With the timing used, quantities are better interpreted as quantities of producing plants with the implicit assumption that once a firm has invested in plants it produces at full capacity in all states. With this interpretation, marginal costs are long term marginal costs that comprise both fixed capacity costs and variable production costs. Issues related to plant flexibility and the ratio between capacity costs and variable costs are not considered. Note that it is also implicitly assumed that the firm can borrow capital at a risk-free rate.

Output price risk is not explicitly introduced, but, thanks to the additivity of the framework, one can consider that it is included in marginal cost risks θ_1 and θ_2. Output price risk could explain a positive correlation between the random variables θ_1 and θ_2. This aspect will be further discuss when applying the framework to the choice between nuclear and CCGT in an electricity markets. Furthermore, the random variables represented risks but they could also be interpreted as representing the time variability of costs or output price over the life of the plant. In such case, the firm is assumed to be averse to profit variability. Both phenomena, randomness and variability, are generally simultaneously at stake, and they surely are not equivalent from the firm's perspective. Such distinctions are not considered here.

3 The supply curve

In this section, the supply of a single price-taking firm is described, the subscript i is dropped to alleviate notations. The firm chooses the quantity of each technology to maximize (3). At an interior solution, the marginal increase of expected profit is equalized with the marginal increase of weighted variance for each technology:

$$p - c_t = \frac{\lambda}{2}\frac{\partial}{\partial q_t}\text{var}(\pi), t = 1, 2. \tag{4}$$

The right-hand side is the effect of an increase of production on the variance of the firm's profit. With independently distributed risks, this term is positive for all production and null if production is null. These two features could be reversed with correlated risks. First, if risks are negatively correlated, the variance of profit could decrease with respect to production with a technology. If the firm produces a strictly positive quantity with a particular technology, (e.g. technology 1), then an increase of production with another technology (e.g. technology 2) can reduce the overall risk faced by the firm because the specific risk of technology 2 is negatively correlated with the risk of technology 1. Thus, production with technology 2 is used to hedge production with technology 1. One consequence is that it is possible that the firm invests in a technology even if the output price is lower than the expected marginal cost of this technology (cf Proposition 1 below).

Second, the right–hand side of (4) is not necessarily null at zero. If costs are positively correlated, the marginal effect of production on variance is strictly positive even at zero if the firm produces a strictly positive quantity with the other technology. In such a case, it is possible that the firm does not invest in a technology even if the price is above the expected marginal cost of that technology (cf Propositions 2 and 3).

If the firm invests in both technologies, quantities satisfy the pair of first order conditions, from (4):

$$p - c_t = \lambda \left(\sigma_t^2 q_t + \sigma_{12} q_s \right) = \lambda \sigma_t^2 \left(q_t + \rho \frac{\sigma_s}{\sigma_t} q_s \right), t = 1, 2. \tag{5}$$

The second term of the right-hand side represents the effect of correlation.[5] If costs are positively correlated, the production with one technology decreases with respect to the production of the other technology, while the price is maintained fixed. This is so because an increase of production with one technology increases the risk faced by the other technology production. This relation is reversed if marginal costs are negatively correlated.

The supply of the firm and the share of each technology depends on the value of the variances and the correlation of the marginal costs. Several cases should be distinguished whether the covariance is smaller than none or one of the variances and whether it is positive.[6] Before distinguishing those cases a general characteristic of the technology portfolio could be established.

[5]For the reader familiar with the Capital Asset Pricing Market (Sharpe, 1964) these first order conditions translates into

$$p - c_t = \lambda \text{cov}(\theta_t, -\pi) = \lambda \text{var}(\pi) \beta_t$$

where $\beta_t = \text{cov}(\theta_t, -\pi)/\text{var}(\pi)$.

[6]It is not possible that the covariance be larger than both variances because $2\sigma_{12} \leq \sigma_1^2 + \sigma_2^2$.

Lemma 1 *The share of the efficient technology, q_1/q, decreases with respect to the output price.*

When the output price increases, whatever the precise characteristics of the distribution of random components, the firm increases its total production and progressively invests in an increasing share of the inefficient technology for hedging purposes.

To precisely analyze the composition of the mix, two threshold prices are worth introducing:

$$p_1 = \frac{\sigma_2 c_1 - \rho\sigma_1 c_2}{\sigma_2 - \rho\sigma_1}, \text{ and } p_2 = \frac{\sigma_1 c_2 - \rho\sigma_2 c_1}{\sigma_1 - \rho\sigma_2}. \tag{6}$$

These prices are derived (cf appendix A) from expressions of the solutions of equations (5). The price p_t nullifies the expression of the production with technology t. The precise composition of the firm's supply depends on the characteristics of the distributions of the risks and three cases should be distinguished.

Proposition 1 *If $\rho \leq \min\{\sigma_1/\sigma_2, \sigma_2/\sigma_1\}$, then:*

- *for $p < p_2$, the firm only invests in technology 1, $q_2 = 0$;*
- *for $p \geq p_2$, the firm invests in both technologies and both quantities increases with respect to the output price.*

Furthermore, the threshold price p_2 at which the firm starts investing in technology 2 is lower than its expected marginal cost if and only if risks are negatively correlated, i.e.

$$p_2 < c_2 \Leftrightarrow \sigma_{12} < 0.$$

The proof is in appendix A. For a small output price, the firm only invests in the efficient technology, while for a larger one the firm diversifies its technology portfolio by investing in the second technology. The price at which the firm starts investing in the inefficient technology is lower than its expected cost if costs are negatively correlated. In that case, to reduce its risk, the firm invests in a technology that is not only inefficient but that also has an expected cost below the output price. Such situation occurs if and only if technology risks are negatively correlated. Without such correlation there is the usual result that the firm invests only if expected return is strictly positive. However, with positive correlation the threshold price is higher than the expected cost which means that there is a range of prices that are strictly larger than the expected cost of the technology 2 but that do not trigger investment in that technology.

Proposition 2 *If $\rho > \sigma_2/\sigma_1$ then $\sigma_1 > \sigma_2$ and $p_2 < p_1$ and:*

- *for $c_1 \leq p \leq p_2$ the firm only invests in technology 1, $q_2 = 0$;*
- *for $p_2 \leq p \leq p_1$ the firm invests in both technologies;*
- *for $p_1 \leq p$ the firm only invests in technology 2.*

The proof is in appendix A. When the risk associated with the efficient technology is greater than the risk associated with the inefficient one and the correlation between both technologies is sufficiently important, the technology mix of the firm changes dramatically as the price increases. The supply curve of the firm is depicted on Figure 1. For a small price, the firm invests only in the efficient technology. It then starts investing in the second technology, and it progressively increases the quantity invested in this technology while decreasing the quantity invested in the efficient technology up to the point where for sufficiently large prices the firm only invests in the inefficient technology. When the price is large, not only does the firm invest in an inefficient technology, but it completely stops investing in the efficient one. In such a case, risk explains that an efficient technology is driven out of the firm's portfolio. Because of the positive correlation between the two technologies, the risk associated with the efficient technology is magnified and investing in this technology is not worth because it increases the risk associated with the other kind of plants. Even very high expected returns on the efficient technology plants cannot justify investing in this technology because of portfolio effects.

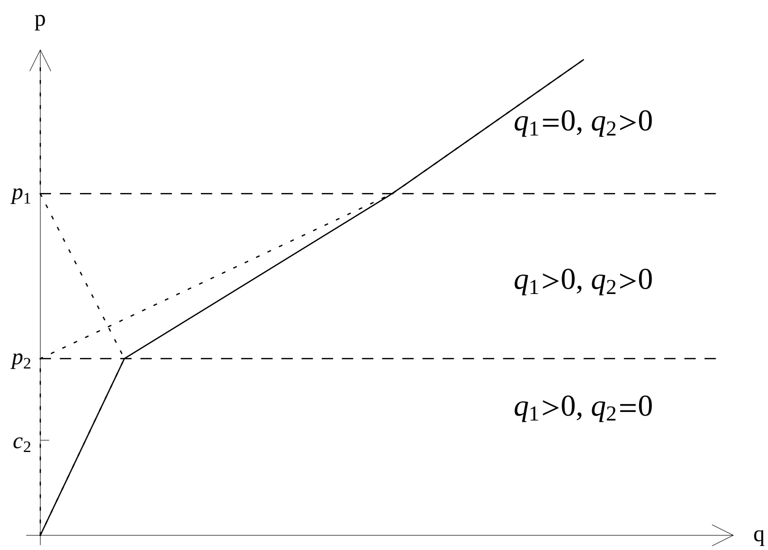


Figure 1: The supply curve with $\rho > \sigma_2/\sigma_1$.

Proposition 3 *If $\sigma_1 < \sigma_2$ and $\rho > \sigma_1/\sigma_2$ then the firm only invests in technology 1 for any price above c_1.*

The proof is in appendix A. If the risk associated with the inefficient technology is large and both risks are highly correlated, the firm only invests in the efficient technology whatever the output price. It is the conjunction of the two features–high variance and high correlation– that explains why diversification into the inefficient technology is not interesting because investing in this technology increases the risk faced by the efficient plants.

Correlation plays a critical role on the supply curve and technological mix of the firm. Let us now investigate the consequences of a change of correlation. For any given couple of quantities, an increase of correlation increases the aggregate risk and also the marginal effect of each technology on that risk. However, there are cross effects that should be investigated before concluding a negative effect of correlation on investment. Correlation has a non-null effect only if both technologies are used. In such a situation, from equations (5) the effect of a marginal increase of correlation is as follows:

$$\frac{\partial q_t}{\partial \rho} = -\frac{\sigma_s}{\sigma_t} q_s - \rho \frac{\sigma_s}{\sigma_t} \frac{\partial q_s}{\partial \rho} \tag{7}$$

where there is a direct negative effect related to the increase of risk and an indirect one due to substitution among technologies. If the correlation is positive,a decrease of the quantity of technology 2 is compensated by an increase of technology 1. From 7 the portfolio modification is:

$$\frac{\partial q_t}{\partial \rho} = \frac{1}{1-\rho^2}\left[-\frac{\sigma_s}{\sigma_t} q_s + \rho q_t\right] \tag{8}$$

The first term represents the direct negative effect of correlation and the second term represents the indirect cross effect. When the correlation is negative this cross effect is negative and both quantities decreases but when the correlation is positive, the overall effect is ambiguous. The consequence on the total production is as follows:

$$\frac{\partial q}{\partial \rho} = \frac{1}{1-\rho^2}\left[\left(\rho - \frac{\sigma_1}{\sigma_2}\right) q_1 + \left(\rho - \frac{\sigma_2}{\sigma_1}\right) q_2\right]. \tag{9}$$

This could be positive only in the situation described by proposition 2. When both the risk associated to technology 1 and correlation are sufficiently important, there is a range of prices where q_1 is sufficiently small and q_2 is sufficiently large for this expression to be negative. Therefore, even though correlation increases both the variance of the firm's profit and the effect of productions on this variance, the total production might increase when correlation increases. However, the increase of the total production only happens for a small set of parameters values; in other cases, the intuitive result that production decreases with correlation holds.

4 Market equilibrium

Perfect competition

If firms are price takers, the equilibrium price clears the market so that supply equals demand. Given the linearity of the model, a well-known property of the CAPM (Sharpe, 1991) is satisfied in the present framework: for any given price, the coefficient of risk aversion of a firm does not influence the composition of its portfolio but only the total quantity it produces. Therefore, for a given price, all firms choose similar portfolios but differ with respect to their total production.

With price-taking firms the total supply of the n firms is similar to the supply of a single producer with risk aversion Λ defined by

$$\Lambda = \left[\sum_{i \in I} (1/\lambda^i) \right]^{-1}. \tag{10}$$

This parameter can be interpreted as a measure of the aggregate risk aversion of all firms. Each firm i's investment in a technology represents a share Λ/λ^i of the total quantity invested in the sector. Alternatively said, the sectoral technology portfolio is optimal for each firm, that is, 'optimal' in the sense that it maximizes the firm's utility 3.

Any entry of a new firm in the industry is equivalent to a reduction of the sectoral risk-aversion parameter Λ. It is *as if* the supply side became less risk averse. For a given price, a change of the risk-aversion parameter does not affect the composition of the portfolio but rather the aggregate quantity supplied. With an endogenous price, this change of supply modifies the portfolio indirectly via the output price.

Corollary 1 *An increase in the number of firms or a decrease of a firm's risk-aversion decreases the output price and increases the share of the efficient technology in each firm's portfolio and in the total portfolio.*

Though the result of this corollary is intuitive, the mechanism behind it is not. An increase in the number firms (a decrease of the industry risk-aversion) does not directly correct the mix toward the efficient technology but indirectly via a reduction of the output price. When the number of firms grows the portfolio converges toward the efficient one, $Q_2^* = 0$ and $p(Q_1^*) = c_1$, because the output price converges toward the marginal cost of the efficient technology.

Imperfect Competition

With imperfect competition, each firm is able to anticipate the effect of its investment or production choice on the price. Each firm $i \in I$ maximizes $U(p(Q), q_1^i, q_2^i)$. At equilibrium each firm's supply satisfies the following two first order conditions:

$$p + p'q^i = c_t + \frac{\lambda^i}{2} \frac{\partial}{\partial q_t^i} \mathrm{var}(\pi_i), \text{ for } t = 1, 2, \ i \in I \tag{11}$$

Compared to the perfectly competitive outcome, each firm faces a different marginal revenue at equilibrium. The marginal revenue of a firm is lower the larger its market share. Accordingly, given the total production, and the less risk-averse a firm is, the more it produces. Therefore, firms with lower risk aversion not only produce more but also face lower marginal revenues, and from Lemma 1, their portfolio is more efficient.

Proposition 4 *For $i, j \in I$,*
$\lambda^i \leqslant \lambda^j$ *if and only if* $q^i \geqslant q^j$ *and* $\frac{q_1^i}{q^i} \geqslant \frac{q_1^j}{q^j}$.

The proof is in Appendix B. Contrary to perfect competition, with imperfect competition the firms' investment choices are different with respect to more than just their size. The less risk averse firms produce more, and facing a lower marginal revenue, thier portfolios are more efficient.

Corollary 2 *For $i \in I$, a decrease of λ^i has the following consequences:*

(i) it increases the production of firm i;

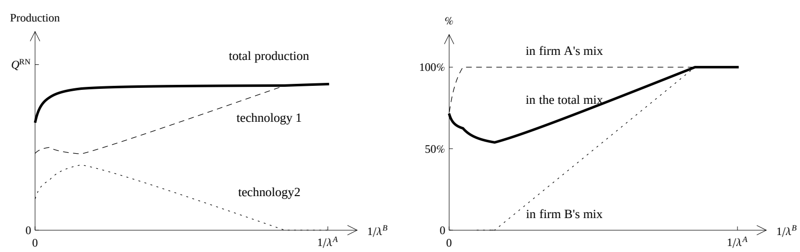
(ii) it reduces the production of all other firms;

(iii) it increases the share of the efficient technology in each firm's portfolio;

(iv) it increases or decreases the share of the efficient technology in the overall portfolio.

The portfolio of a firm is a function of the production of its competitors. The larger this production, the smaller the production of the firm, but the more efficient its portfolio. With imperfect competition, at equilibrium the larger firms have more efficient portfolios than their rivals, but an increase in the production they face, make them smaller and more efficient. The reduction of the risk-aversion of a firm makes every firm more efficient, but it has an ambiguous effect on the overall portfolio. It is possible that, following such a change, even though all firms' portfolios contain a larger share of technology 1, the overall portfolio has a lower share of the technology.

Figure 2 illustrates this point in a duopoly with a linear price function $p = 1 - Q$. There are two firms denoted A and B, firm A is less risk-averse than firm B, i.e., $\lambda^A < \lambda^B$. If the risk-aversion of firm A decreases, it unambiguously increases the share of technology 1 in the overall portfolio.[7] On the contrary, if the risk-aversion of firm B decreases, it has a non-monotonic effect on the overall portfolio. Figure 2 represents the evolution of several relevant variables as the risk-aversion of firm B decreases. In Figure 2(a), the quantities invested in technologies 1 and 2 and their sum are depicted, and Figure 2(b) depicts the evolution of the share of technology 1 in each firm portfolio and in the overall portfolio. As shown in the figures, firm B becomes less risk-averse, and the share of technology 1 increases in both firms portfolios; however, its share in the overall portfolio first decreases before increasing. The reduction of the share of technology 1 in the overall portfolio is due to the reduction of the total production of firm A. Although, the portfolio of firm A becomes increasingly more composed of technology 1, the reduction of its total production overcompensates for this change.



(a) The total production

(b) The share of technology 1 in the overall mix and in each firm's ones.

Figure 2: Evolution of the technology mix in a duopoly as the risk-aversion of a firm decreases (firm B)

Figure 2 also illustrates the possibility of a full specialization of the industry with both firms using different technologies. For highly risk-averse firm B, this firm only uses technology 2 while firm A uses both technologies. Firm A then specializes in technology 1, while firm B continues to use only technology 2. Accordingly, the industry is fully specialized, and firms use different technologies. As firm B becomes less risk-averse, it starts using

[7]This is true in a duopoly, but not necessarily in an oligopoly. If there more than two firms, a decrease of the risk-aversion of the less risk-averse firm has an ambiguous effect in general.

technology 1, and, eventually, it, too, specializes in technology 1. It is difficult and fastidious to find analytical conditions, even with a linear price function, that are necessary and sufficient for firms to use different technologies. However, we do know that the conditions of Proposition 2 should be satisfied for full specialization, and it is possible to get a sufficient condition in the general case.

Corollary 3 *If $\rho > \sigma_2/\sigma_1$, and, if the price with a risk-neutral monopoly is larger than p_1, then, there are λ^A and λ^B, with $\lambda^A < \lambda^B$, such that in a duopoly $I = \{A, B\}$ both firms produce a strictly positive quantity, and firm A (resp. B) only uses technology 1 (resp. 2).*

If the price with a risk-neutral monopoly is larger than the threshold price p_1, then for small λ^A, a monopoly with a risk-aversion λ^A results in a price that is also larger than p_1. This ensures that for a large λ^B, firm B will be sufficiently small such that its marginal revenue is above p_2, and the firm is specialized. It is always feasible to calibrate a price function that satisfies this condition.

We conclude this section with a brief discussion on the effect of the entry of firms. In the perfectly competitive setup the entry of a new firm is equivalent to the reduction of the risk-aversion of one firm. With imperfect competition, this is also true and ambiguities, like those describes above, can arise. Whereas the entry of a firm increases the total production and the share of the efficient technology in each firm portfolio, its effect on the overall portfolio is ambiguous if firms' risk-aversions are sufficiently heterogeneous. For instance, if there is one firm with a low risk-aversion, firm A, that is facing n_B more risk-averse rivals that are identical, an increase in the number of these competitors has an effect qualitatively similar to the reduction of the risk-aversion of firm B in the previous example. With sufficiently heterogeneous firms, the large firm is initially in a position of monopoly and it produces using both technologies. As risk-averse competitors start entering the industry, they are first specialized in technology 2.Although, these initial entries make firm A increases the share of technology 1 in its portfolio, they reduce the share of technology 1 in the aggregate mix. Thus, the share of the efficient technology in the industry portfolio is U-shaped, and eventually goes to 1.

5 Nuclear versus gas

The framework could be specified to suit the issue of investment in nuclear and CCGT plants in an electricity market. Our simple model does not account for plant flexibility, that is, the possibility for a producer to reduce or stop its production if the price of electricity is low. This flexibility explains that even without any risk consideration there is an optimal technology mix to produce electricity for a variable or random consumer surplus.[8] Our analysis is better interpreted as a competition between base-load technologies, i.e., technologies used to produced throughout the entire year.

The price of electricity, the cost of a nuclear plant and the cost of CCGT are all random. The risks associated with the cost of a nuclear plant is relatively specific and unrelated to the risks associated with the electricity and gas prices; in particular, these risks concern investment and O&M (operation and maintenance) costs. The former are well illustrated by the frequent revisions in the cost the EPR (European, or Evolutionary, Pressurized Reactor), a new and complex technology. Other existing technologies are more mastered and not subject to a similar uncertainty. However, the earthquake and the following Tsunami in Japan and their effects on the reactors in Fukushima induced a likely change in the O&M costs for all world wide existing reactors due to more stringent safety regulations. Furthermore, the uncertainty surrounding the life span of plants and the costs of their decommissioning can also be viewed as a risk associated to the annualized cost of nuclear power production. Concerning CCGT, the two most important components of these risks come from the uncertainty surrounding the price of gas and the uncertainty surrounding the price of CO_2 emissions. Roques et al. (2008) consider that the cost of CCGT is positively correlated with the price of electricity. Several reasons can explain this positive correlation. First, if the variable cost of CCGT plants determines the price of electricity the majority of the time, these are naturally correlated. Given that, in the present framework, it is assumed that capacity is always fully used it is not the variable cost of new plants that could determine the electricity price but possibly the variable cost of less efficient gas plants previously built. Second, the demand for electricity and the demand for gas both are linked to the same fundamental variables, such as weather. And third, the positive

[8] The composition of this mix and its relation to electricity pricing has been analyzed in the so called "peak-load pricing" literature (see Crew et al., 1995, for a review) and recently reformulated in the context of competition by Joskow and Tirole (2007).

correlation can also be because electricity and gas are substitutable inputs for households and industries.

Let us denote $c_n + \epsilon_n$ and $c_g + \epsilon_g$ as the random costs of a nuclear plant and a CCGT, respectively. The price of electricity is also assumed random: $p + \epsilon$. Thus, compared to the previous framework, if nuclear is more (resp. less) efficient than CCGT, it corresponds to technology 1 (resp. 2) and CCGT to technology 2 (resp. 1), and random components are $\theta_1 = \epsilon_n - \epsilon$ (resp. $\theta_2 = \epsilon_n - \epsilon$) and $\theta_2 = \epsilon - \epsilon_g$ (resp. $\theta_1 = \epsilon - \epsilon_g$). The uncertainty surrounding the price of electricity is formally equivalent, given the linearity of the framework, to an uncertainty surrounding both technologies' costs. It is assumed that the risk associated to nuclear is not correlated to electricity prices and CCGT cost:

$$\text{cov}(\epsilon_n, \epsilon) = 0 \text{ and } \text{cov}(\epsilon_n, e_g) = 0 \tag{12}$$

With this transposition of the framework, the variances associated with each technology are the following:

$$\text{var}(\epsilon_n - \epsilon) = \text{var}(\epsilon) + \text{var}(\epsilon_n) \tag{13}$$
$$\text{var}(\epsilon_g - \epsilon) = \text{var}(\epsilon) + \text{var}(\epsilon_g) - 2\text{cov}(\epsilon, \epsilon_g) \tag{14}$$

and the covariance of these risks are the following:

$$\text{cov}(\theta_1, \theta_2) = \text{cov}(\epsilon_n - \epsilon, \epsilon_g - \epsilon) = \text{var}(\epsilon) - \text{cov}(\epsilon, \epsilon_g). \tag{15}$$

The price uncertainty induces a positive correlation between technologies' returns. This correlation between the returns of technologies is decreasing with respect to the correlation between the price of gas and the price of electricity.

Corollary 4 *If $c_n < c_g$ and $cov(\epsilon, \epsilon_g) \geq var(\epsilon_g)$, then for a large expected electricity price, $p > p_1$, a price-taking firm only invests in CCGT. The threshold price p_1 is*

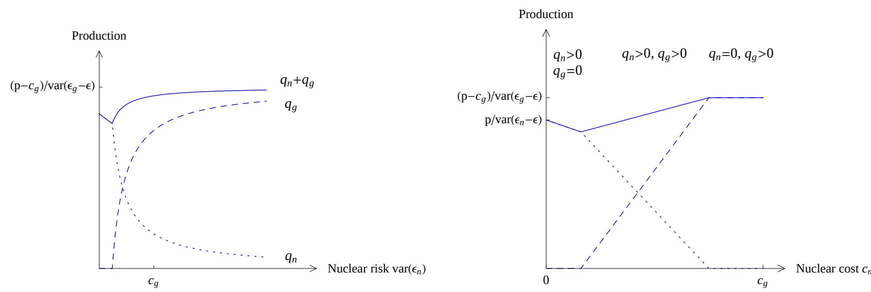
$$p_1 = \frac{(var(\epsilon) - cov(\epsilon, \epsilon_g))\, c_g - (var(\epsilon_g) + var(\epsilon) - 2cov(\epsilon, \epsilon_g))\, c_n}{cov(\epsilon, \epsilon_g) - var(\epsilon_g)} \tag{16}$$

If the correlation between gas and electricity prices is sufficiently strong, firms do not invest in nuclear even if it is the most efficient technology.

The condition on the risks depends only on the covariance between CCGT cost and electricity prices and the variance of the CCGT cost. The risk associated with the nuclear technology does not intervene in this condition. The threshold does not depend on the nuclear risk either. Thus, if an industry is in the configuration described by the Lemma, it is fully specialized in gas, and a reduction of the risk associated to nuclear power would not modify the industry equilibrium.

The effect of a change of the nuclear risk $\mathrm{var}(\epsilon_n)$, has interesting consequences. Such a change is depicted in Figure 3(a) for the situation described by the Lemma $c_n < c_g$ and $\mathrm{cov}(\epsilon, \epsilon_g) > \mathrm{var}(e_g)$ and a fixed price between p_2 and p_1. For such a price, the industry is diversified and invests in both technologies. As evidenced, an increase in the variability of the nuclear cost induces a reduction of the investment into nuclear plant and a rise in the investment into CCGTs. The latter change dominates and the overall effect on the industry supply is positive. This surprising result is due to the correlation between gas and electricity prices. If this correlation is greater than the variance of the gas price, then any reduction of the nuclear production induces an overcompensating increase in CCGT production (see the first order condition 5).

A second surprising consequence of the condition of Corollary 4 relates to the effects of a change to the cost of nuclear plants. These effects are depicted in Figure 3(b), for a fixed expected electricity price above c_g. For a small nuclear cost, the industry is fully specialized into nuclear production, and its supply is decreasing with respect to the nuclear cost until it becomes diversified when $p_1 = \mathbb{E}p$. From this point, the nuclear production decreases and the gas production increases sufficiently to ensure an increase of the total production. Finally, for for large nuclear cost, the industry specializes into gas and the cost of nuclear plants no longer influences the supply.



(a) The effect of the nuclear risk var(ϵ_n)

(b) The effect of the nuclear expected marginal cost c_n

Figure 3: Evolution of the supply for a fixed price as a function of the characteristic of nuclear technology

Figure 3 is obtained with specific values of parameters and a given price. However, the results of comparative static could be obtained with a general cost function.

Corollary 5 *If $cov(\epsilon_g, \epsilon) > var(\epsilon)$, and, if the equilibrium price is strictly between p_1 and p_2, then, either an increase of the marginal cost of nuclear c_n, or an increase of the risk associated to nuclear $var(\epsilon_n)$, induces an increase of the total production and a decrease of the price of electricity.*

It is difficult to draw policy recommendations from this analysis given that no market failures have been identified. If the risk-aversion behavior of firms were related to a market failure, correcting this market failure could enhance the welfare. However, it may be optimal that firms behave in a risk-averse fashion. For instance, if there are transactions costs that explain markets incompleteness, to "complete" markets by regulation may be too costly and inefficient. However, the analysis could still help to understand the consequences of regulations targeted to help firms invest in nuclear plants. The analysis provides a double-edged argument. On the one hand, the analysis shows that risk can theoretically explain that firms do not invest in nuclear plants even though it is the most efficient technology. It then seems justified to help nuclear technology. On the other hand, if conditions are met for the first result to hold, a regulation that either reduces the cost or the risk of the nuclear technology can have unexpected adverse consequences. As stated by Corollary such policies could reduce the overall investment in power producing plants.

6 Conclusion

In this article, the technology portfolio of an industry of risk-averse producers has been analyzed in depth. The influence of correlation between technologies risks has been particularly stressed. It has been shown that this correlation has a crucial influence on the equilibrium portfolio of firms. In particular, this correlation can deter firms from investing in an efficient technology and explain the full specialization of an industry in an inefficient (i.e. with a larger expected marginal cost) technology.

Furthermore, the analysis of the market equilibrium under perfect competition reveals that all price-taking firms have the same portfolio, but they differ with respect to their size. Furthermore, the more firms there are the larger the share of the efficient technology into each firm and into the industry portfolio. These results are deeply modified with imperfect competition. In particular, with imperfect competition firms with different risk-aversion have different portfolios and, theoretically, risk-aversion can explain that each firm is specialize into one technology. Additionally, even though a reduction in the risk-aversion of one firm increases the share of the efficient technology in each firm portfolio, it can possibly reduce the share of this technology in the overall portfolio.

The analysis was then used to discuss the choice between nuclear and CCGTs for base-load production in an electricity market. If the cost of CCGT and electricity prices are sufficiently correlated, the previous results apply. If nuclear technology were cheaper than CCGTs risk could nevertheless explain a full specialization of the industry in CCGTs. Furthermore, the effect of the nuclear risk and expected costs are surprising, as an increase of any of these quantities can induce an increase in the industry's total production.

A Supply curve

Preliminary results

The two first order conditions (4) can be written:

$$\lambda \begin{bmatrix} \sigma_1^2 & \sigma_{12} \\ \sigma_{12} & \sigma_2^2 \end{bmatrix} \begin{bmatrix} q_1 \\ q_2 \end{bmatrix} = \begin{bmatrix} p - c_1 \\ p - c_2 \end{bmatrix} \tag{17}$$

Let denote x_1 and x_2 the solutions of these equations without positivity constraints:

$$\left[\begin{array}{c} x_1 \\ x_2 \end{array}\right] = \frac{1}{\lambda\Delta}\left[\begin{array}{c} \left(\sigma_2^2-\sigma_{12}\right)(p-c_1)+\sigma_{12}\left(c_2-c_1\right) \\ \left(\sigma_1^2-\sigma_{12}\right)(p-c_1)-\sigma_1^2\left(c_2-c_1\right) \end{array}\right] \tag{18}$$

where,

$$\Delta = \sigma_1^2\sigma_2^2-\sigma_{12}^2 = \sigma_1^2\sigma_2^2\left(1-\rho^2\right). \tag{19}$$

The thresholds prices p_1 and p_2 in (6) respectively nullify x_1 and x_2. Two useful expressions of these prices are:

$$p_1 = c_1 - \frac{\rho\sigma_1}{\sigma_2-\rho\sigma_1}(c_2-c_1) \text{ and } p_2 = c_1 + \frac{\sigma_1}{\sigma_1-\rho\sigma_2}(c_2-c_1). \tag{20}$$

If (q_1, q_2) maximizes the firm's profit subject to the constraints $q_t > 0$ for $t = 1, 2$, then for $p > c_1$ the following equivalences hold (from the first order conditions of the constrained maximization):

$$q_2 = 0 \Leftrightarrow x_2 \leq 0, \text{ and, } q_1 = 0 \Leftrightarrow p \geq c_2 \text{ and } x_1 \leq 0$$

. Thus,

Lemma 2 *The quantities $q_1(p, \lambda)$ and $q_2(p, \lambda)$ that maximizes the firm's objective (3) are:*

- *if $x_2 \leq 0$ then $q_2 = 0$ and $q_1 = (p-c_1)/(\lambda\sigma_1^2)$;*
- *if $x_2 \geq 0$ and $x_1 \leq 0$ then $q_1 = 0$ and $q_2 = (p-c_2)/(\lambda\sigma_2^2)$;*
- *if $x_1 > 0$ and $x_2 > 0$ then $q_1 = x_1$ and $q_2 = x_2$.*

Proof of lemma 1

Let us show that $q_1(p,\lambda)/\left(q_1(p,\lambda)+q_2(p,\lambda)\right)$ is increasing with respect to p. This function if continuous and differentiable by parts because q_1 and q_2 are. For $p > c_1$ three situations can arise, either both quantities are strictly positive or only one of them. In the latter case the share of technology 1 is constant w.r.t. p (it is either 1 or 0). In the former case the two first order conditions 4 are satisfied and both quantities are equal to x_1 and x_2. Taking the derivative of the equations 18 gives

$$\begin{bmatrix} \partial q_1/\partial p \\ \partial q_2/\partial p \end{bmatrix} = \frac{1}{\lambda\Delta} \begin{bmatrix} \sigma_2^2 - \sigma_{12} \\ \sigma_1^2 - \sigma_{12} \end{bmatrix} \tag{21}$$

And the sign of the derivative of the share of technology 1 in the firmr's portfolio is the sign of (the numerator of its derivative):

$$\frac{\partial q_1}{\partial p} q_2 - \frac{\partial q_2}{\partial p} q_1 \tag{22}$$

which is equal to (from 18 and 21 and the expression of Δ 19):

$$\frac{1}{(\lambda\Delta)^2} \left[\left(\sigma_2^2 - \sigma_{12}\right)\left(-\sigma_1^2\right) - \left(\sigma_1^2 - \sigma_{12}\right)\sigma_{12} \right] = \frac{1}{\lambda^2} > 0. \tag{23}$$

Proof of Proposition 1

If $\rho < \min\{\sigma_1/\sigma_2, \sigma_2, \sigma_1\}$ then:

- $p_1 < p_2$:
  - if $\rho \geq 0$ then from (20) $p_1 < c_1 < p_2$;
  - if $\rho < 0$ then, $(-\rho)(\sigma_1 - \rho\sigma_2) < \sigma_2 - \rho\sigma_1$ because $\rho^2 < 1$, and from (20), using $\rho < 0$, $p_1 < p_2$.
- x_t, for $t = 1, 2$, is increasing with respect to p because $\sigma_t^2 > \sigma_{12}$;

Then, for $p \in (c_1, p_2]$, $x_2 \leq 0$ so q_2=0 and $q_1 > 0$ by Lemma 2; for $p \geq p_2$ then $p \geq p_1$ so $x_1 > 0$ and $q_t = x_t$ for $t = 1, 2$ and both quantities increase as the price increases. Furthermore, from (6) $p_2 = c_2 + \rho(c_2 - c_1)\sigma_2/(\sigma_1 - \rho\sigma_2)$ so $p_2 < c_2$ if and only if $\rho < 0$.

Proof of Proposition 2

If $\rho > \sigma_2/\sigma_1$ then $\sigma_2 < \sigma_1$ because $\rho < 1$. And, from 6

- $p_2 < p1$: $\rho(\sigma_1 - \rho\sigma_2) > \rho\sigma_1 - \sigma_2)$ because $0 < \rho < 1$; then, $p_2 < p_1$ from the expressions (20) of p_1 and p_2 and because $\sigma_1 - \rho\sigma_2 > 0$ and $\rho\sigma_1 - \sigma_2 > 0$.
- the proposition follows from the application of Lemma 2.

Proof of Proposition 3

If $\rho > \sigma_1/\sigma_2$ then $\sigma_1 < \sigma_2$ and $x_2 < 0$ for any p larger than c_1 from (18) and by Lemma 2 the firm only invests in technology 1.

B Market Equilibrium

Let us introduce a new notation to ease the exposition, $\Phi(p)$ is the total production of a firm with risk aversion 1 facing a price p:

$$\Phi(p) = q_1(p, 1) + q_2(p, 1). \tag{24}$$

This function is increasing with respect to p:

$$\Phi' = \frac{1}{\Delta}\left[\sigma_1^2 + \sigma_2^2 - 2\sigma_{12}\right] > 0.$$

Proof of Corollary 1

the quantity produced with each technology by a price-taking firm facing price p, with risk aversion λ are $q_1(p, \lambda)$ and $q_2(p, \lambda)$. From Lemma 2 these functions satisfies:

$$q_t(p, \lambda) = \frac{1}{\lambda} q_t(p, 1) \text{ for } t = 1, 2 \tag{25}$$

At the industry level, for any price p the supply of the industry with technology $t = 1, 2$ is:

$$Q_t = \sum_{i \in I} q_t(p, \lambda^i) = q_t(p, 1) \sum_{i \in I} \frac{1}{\lambda^i} = \frac{1}{\Lambda} q_t(p, 1) = q_t(p, \Lambda) \tag{26}$$

At the market equilibrium, the price p^* satisfies:

$$p^* = P(q_1(p^*, \Lambda) + q_2(p^*, \Lambda)) = P(\Phi(p^*)/\Lambda). \tag{27}$$

taking the derivative w.r.t. Λ:

$$\frac{\partial p^*}{\partial \Lambda} = -\frac{P'}{\Lambda^2}\Phi + \frac{P'}{\Lambda}\Phi' \frac{\partial p^*}{\partial \Lambda} \tag{28}$$

Then, the sum Φ is increasing with respect to p (from 21), P' is negative, so, p^* is increasing with respect to Λ.

A reduction of the risk aversion of one firm or the entry of a new firm are both equivalent to a reduction of Λ and induce a reduction of the equilibrium price. From Lemma 1, the share of technology 1 increases in each firm portfolio and in the industry portfolio.

Proof of Proposition 4

Let us first show that there is a unique Cournot equilibrium. Let us denote $R(Q, \lambda)$ the (unique) solution of the equation:

$$R = \frac{1}{\lambda}\Phi(P(Q) + P'(Q)R) \tag{29}$$

the solution of this equation is unique because the right hand side is continuous and decreasing w.r.t. R. $R(Q, \lambda)$ is the production of a firm with risk-aversion λ when total production is Q. This function is decreasing w.r.t to Q because the right hand side is decreasing w.r.t. Q (because $P' + P''R < 0$). It is differentiable by part and

$$\frac{\partial R}{\partial Q} = -\frac{\Phi'}{\lambda}(P' + P''R) + \frac{\Phi'}{\lambda}P'\frac{\partial R}{\partial Q} \tag{30}$$

At a Cournot equilibrium the total production Q and each firm production q^i satisfy $q^i = R(Q, \lambda^i)$. The total Cournot production is the solution of the equation:

$$Q = \sum_{i \in I} R(Q, \lambda^i). \tag{31}$$

This equation as a unique solution (the R.H.S. is decreasing), so the Cournot equilibrium is unique: each firm's production are the unique solutions of

$$q^i = R(Q, \lambda^i) \tag{32}$$

$$q^i_t = q_t(P + P'q^i, \lambda^i) = \frac{1}{\lambda^i}q_t(P + P'q^i, 1) \tag{33}$$

The function $R(Q, \lambda)$ is striclty decreasing w.r.t. λ when positive (by differentiation of 29). So,

$$\lambda^i \leqslant \lambda^j \Leftrightarrow q^i \geqslant q^j \tag{34}$$

Then, let us show that

$$\lambda^i \leqslant \lambda^j \Rightarrow \frac{q^i_1}{q^i} \geqslant \frac{q^j_1}{q_j} \tag{35}$$

We proceed by contradiction and assume that there are two firms $i, j \in I$, $i \neq j$ such that $\lambda^i < \lambda^j$ and $q_1^i/q^i < q_1^j/q^j$. By Lemma 1 $q_1(p,1)/\Phi(p)$ is increasing w.r.t. to p, so (by 33) $P + P'q^i > P + P'q^j$ and $q^i < q^j$ a contradiction.

The Proposition follows from 34 and 35.

Proof of Corollary 2

We consider a decrease of the risk aversion of firm $i \in I$. The cournot equilibrium production is the solution of

$$Q = \sum_{j \in I} R(Q, \lambda^j). \tag{36}$$

a decrease of λ^i increase the right-hand-side for all Q, so the total production increases. We prove the three first points of the Corollary

- For firm $j \neq i$, its production $R(Q, \lambda^j)$ decreases because R decreases w.r.t. Q (point (ii)).
- Concerning firm i, its production increases because the total production increases and all other firms production decreases (point(i)).
- The marginal revenue of all firms decreases:
  - for firm i, $P(Q) + P'(Q)q^i$ decreases because Q and q^i increases,
  - for firm $j \neq i$, $P(Q) + P'(Q)q^j$ decreases because q^j decreases and $q^j = \Phi(P + P'q^j)/\lambda^j$, and λ^j remains unchanged and Φ is decreasing.

  So, from Lemma 1, the share of technology 1 in all firms portfolio increases (point(iii)).

C Nuclear versus Gas

Proof of Corollary 4

Corollary 4 is an application of Proposition 2. If $c_n < c_g$ then nuclear corresponds to technology 1 in the general framework, and $\text{cov}(\epsilon, \epsilon_g) \geq \text{var}(\epsilon_g)$ is equivalent to $\rho \geq \sigma_2/\sigma_1$:

$$\rho = \frac{\mathrm{cov}(\epsilon_n - \epsilon, \epsilon_g - e)}{[\mathrm{var}(\epsilon_n - \epsilon)\mathrm{var}(e_g - e)]^{1/2}} = \frac{\mathrm{cov}(\epsilon_n - \epsilon, \epsilon_g - e)}{\mathrm{var}(\epsilon_n - \epsilon)} \frac{[\mathrm{var}(e_n - e)]^{1/2}}{[\mathrm{var}(e_g - e)]^{1/2}}.$$

$$\begin{aligned}
\rho \geq \frac{\sigma_2}{\sigma_1} &\Leftrightarrow \frac{\mathrm{cov}(\epsilon_n - \epsilon, \epsilon_g - e)}{\mathrm{var}(\epsilon_n - \epsilon)} \geq 1 \\
&\Leftrightarrow \mathrm{cov}(\epsilon_n - \epsilon, \epsilon_g - e) \geq \mathrm{var}(\epsilon_n - \epsilon) \\
&\Leftrightarrow \mathrm{cov}'(\epsilon, \epsilon_g) \geq \mathrm{var}(\epsilon_g) \qquad \text{from (15) and (13)}
\end{aligned}$$

Then, by plugging the expressions 13, 14 and 15 into the expression of the threshold p_1 6 its expression is as follows:

$$p_1 = \frac{(\mathrm{var}(\epsilon) - \mathrm{cov}(\epsilon, \epsilon_g))\, c_g - (\mathrm{var}(\epsilon_g) + \mathrm{var}(\epsilon) - 2\mathrm{cov}(\epsilon, \epsilon_g))\, c_n}{\mathrm{cov}(\epsilon, \epsilon_g) - \mathrm{var}(\epsilon_g)}. \tag{37}$$

Proof of Corollary 5

If $c_n < c_g$, nuclear corresponds to technology 1 and CCGT to technology 2 in the general framework. An increase of c_n corresponds to an increase of c_1 and an increase of $\mathrm{var}(\epsilon_n)$ corresponds to an increase of σ_1 with σ_{12} being constant (ρ decreases). We prove that the total production is increasing with respect to c_1 and σ_1 in the general framework. It will prove the corollary.

In the general framework, if both technologies are used, at equilibrium the quantities are $Q_t(p, c_1, \sigma_1)$ for $t = 1, 2$ given by the equations 18 with the industry aggregate risk aversion Λ.

- For a fixed price, an increase of c_1 has the following effects (differentiating 18) :

  $$\frac{\partial Q_1}{\partial c_1} = \frac{-\sigma_2^2}{\Lambda\Delta} \text{ and } \frac{\partial Q_2}{\partial c_1} = \frac{\sigma_{12}}{\Lambda\Delta}$$

  and $\sigma_{12} \geq \sigma_2^2$ (because $\mathrm{cov}(\epsilon, \epsilon_g) \geq \mathrm{var}(\epsilon_g)$), therefore, the total production increases with respect to c_1. Thus, the equilibrium production increases and the market price decreases following an increase of c_1.

- Concerning the effect of an increase of σ_1, it is easier to start from the firs-order conditions 17, differentiating these equations gives:

$$\Lambda \begin{bmatrix} \sigma_1^2 & \sigma_{12} \\ \sigma_{12} & \sigma_2^2 \end{bmatrix} \begin{bmatrix} \partial Q_1/\partial\sigma_1 \\ \partial Q_2/\partial\sigma_1 \end{bmatrix} = \begin{bmatrix} -2\Lambda Q_1 \\ 0 \end{bmatrix} \tag{38}$$

  Then,

$$\begin{bmatrix} \partial Q_1/\partial\sigma_1 \\ \partial Q_2/\partial\sigma_1 \end{bmatrix} = \frac{2Q_1}{\Delta} \begin{bmatrix} -\sigma_2^2 \\ \sigma_{12} \end{bmatrix}. \tag{39}$$

  Therefore, for a given price, the aggregate production is increasing with respect to σ_1 (because $\sigma_{12} > \sigma_2^2$). Consequently, the equilibrium price is decreasing and the equilibrium quantity is increasing with respect to σ_1.

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